

## ORIGINAL ARTICLE

## Proximity to roadways and pregnancy outcomes

Marie Lynn Miranda<sup>1,2</sup>, Sharon E. Edwards<sup>1</sup>, Howard H. Chang<sup>3</sup> and Richard L. Auten<sup>4</sup>

Adverse birth outcomes are associated with exposure to air pollution during pregnancy. Road proximity is a simple, widely available metric for capturing local variation in exposure to traffic-related air pollution. We characterized maternal exposure to traffic-related air pollution during pregnancy using residential proximity to major roadways among 2004–2008 singleton births in NC. Controlling for maternal race, age, education, nativity, marital status, and tobacco use, and season of birth, parity, infant sex, and Census tract-level urbanization and income, we evaluated the association between road proximity and pregnancy outcomes using generalized linear mixed models with a random intercept for each Census tract. Birth weight, birth weight percentile for gestational age, gestational hypertension, and small-for-gestational age were not associated with road proximity; however, women residing within 250 m of a major roadway were at 3–5% increased odds of low birth weight, preterm birth, and late preterm birth compared with women residing beyond 250 m ( $P < 0.05$ ). Our analyses demonstrate an association between proximity to major roadways and pregnancy outcomes using a large sample. Road proximity may represent a relatively straightforward method for assessing maternal risk from exposure to traffic-related air pollution, with results offering guidance for studies that can more accurately characterize air pollution exposures.

*Journal of Exposure Science and Environmental Epidemiology* (2013) **23**, 32–38; doi:10.1038/jes.2012.78; published online 18 July 2012

**Keywords:** air pollution; traffic; road proximity; birth outcomes; birth weight; preterm birth

## INTRODUCTION

Air pollution is linked to many adverse health outcomes, such as asthma, chronic obstructive pulmonary disease, exacerbation of cardiovascular disease, and mortality.<sup>1</sup> Exposure to air pollution during pregnancy may increase the risk of adverse birth outcomes, including low birth weight (LBW), preterm birth (PTB), and small-for-gestational age (SGA).<sup>2,3</sup> These adverse outcomes are in turn associated with increased risk for short-term neonatal mortality and long-term disabilities,<sup>4,5</sup> as well as increased risk of diabetes, obesity, cardiovascular disease, and other health problems in adulthood.<sup>6–9</sup>

This has been examined directly in animal model systems. Exposure of mice during pregnancy to polluted urban air contributes to cardiovascular oxidative stress in adult offspring.<sup>10</sup> Maternal mouse exposure to diesel exhaust or diesel exhaust particulates during pregnancy increased susceptibility of offspring to allergen-mediated<sup>11</sup> or ozone-mediated<sup>12</sup> airway hyperreactivity. Exposure to urban air pollution during pregnancy impaired fetal growth,<sup>13</sup> birth weight,<sup>14</sup> and lung growth in offspring.<sup>15</sup> It is important to point out that the animal model systems are limited by important species differences among the systems, as well as important biological distinctions with humans.<sup>16</sup>

In humans, various methods have been used to estimate individual air pollution exposure, including personal monitoring data, ambient air quality monitoring system data, interpolated and modeled estimates of pollutant levels, and proximity to roadways. Each method has associated benefits and limitations, thus selecting a method for estimating exposures depends on data availability, cost, practicality, sample size, and the outcomes and pollutants of interest.<sup>2</sup>

Air quality data collected by federal and state monitoring networks and road proximity represent relatively low cost and

simple methods for assigning exposure estimates to a study population. Although data from air quality monitoring networks have been widely used in studies of air pollution and birth outcomes,<sup>3</sup> these methods restrict studies to areas with air quality monitors and are not able to take into account local variation in air pollution levels. Traffic-related emissions are significant contributors to locally elevated air pollution levels around highly traveled roadways, with air pollution levels dropping back to background levels beyond 300 m from roadways.<sup>2</sup> Road proximity, therefore, presents a relatively simple and widely available metric that may capture long-term local variation in exposure to the mixture of pollutants that comprise traffic-related air pollution, including particulate matter, ultrafine particles, nitrogen dioxide, and elemental carbon.<sup>2,17</sup> Traffic-related pollutant concentrations can also exhibit substantial spatial heterogeneity such that central monitors cannot be used effectively for exposure assessment in population studies. We note that road proximity may also be associated with noise exposure and lower socioeconomic status.

A number of birth outcome studies using road proximity as a proxy for exposure to air pollution have been conducted in recent years. Although results were not always significant,<sup>17</sup> maternal residence near highways and major roads was associated with PTB,<sup>18–21</sup> LBW,<sup>18,19,22</sup> and SGA.<sup>22,23</sup> These studies, like studies relying on monitoring data, have tended to focus on births in urban areas.

In this study, we used road proximity as a proxy for air pollution exposure across the State of North Carolina, capturing births in both urban and rural settings. This metric for estimating exposure to air pollution allows us to leverage data on birth outcomes in areas that are not covered by air quality monitoring networks and

<sup>1</sup>Children's Environmental Health Initiative, School of Natural Resources and Environment, University of Michigan, Ann Arbor, Michigan, USA; <sup>2</sup>Department of Pediatrics, University of Michigan, Ann Arbor, Michigan, USA; <sup>3</sup>Department of Biostatistics and Bioinformatics, Rollins School of Public Health, Emory University, Atlanta, Georgia, USA; <sup>4</sup>Division of Neonatology, Department of Pediatrics, Duke University, Durham, North Carolina, USA. Correspondence: Dr. Marie Lynn Miranda, Children's Environmental Health Initiative, School of Natural Resources and Environment, University of Michigan, 440 Church Street, 2046 Dana Building, Ann Arbor, MI 48109, USA. Tel.: +734 764 2550.

E-mail: mlmirand@umich.edu

Received 13 December 2011; accepted 11 May 2012; published online 18 July 2012

would thus be excluded from work utilizing more complex exposure estimates.

## MATERIALS AND METHODS

### Birth Data

The North Carolina Detailed Birth Record database contains extensive information on all documented live births occurring in the State of North Carolina, including birth weight, gestational age, plurality, parity, maternal medical complications, congenital anomalies, tobacco and alcohol use, and maternal and paternal demographic characteristics. These data were provided by the North Carolina State Center for Health Statistics under a data sharing agreement and human subjects protocol that permitted the use of individually identifying information including names and addresses.

In this analysis, we considered births occurring in North Carolina during 2004–2008 ( $n = 635,618$ ). We restricted analysis to singleton first through fourth births to non-Hispanic white (NHW), non-Hispanic black (NHB), and Hispanic (H) mothers residing in North Carolina and aged 15–44 years. We excluded records with any reported congenital anomalies, birth weight less than 400 g, gestational age under 24 weeks or over 42 weeks, or any missing covariate data. Under these restrictions, 531,385 births qualified for inclusion.

The residential address at time of delivery for all births meeting the inclusion criteria were street geocoded using ArcGIS 9.3 software (ESRI, Redlands, CA, USA). We were able to successfully geocode 88.2% of qualifying births, resulting in a final data set consisting of 468,517 births. Among the unmatched records, not used in the analysis, more than half did not provide a residential address on the birth certificate (among those with a residential address, our geocoding rate was 94.2%). The residential addresses of the remaining unmatched records were not able to be located within the reference street data. Unmatched records were more likely to be unmarried, report tobacco use, have lower educational attainment, be younger, be of H or NHB race, and reside in rural or low-income areas.

### Road Proximity Data

Maternal exposure to traffic-related air pollution during pregnancy was characterized by determining the linear distance between geocoded residential address at delivery and the nearest major roadway. Geocoded addresses were overlaid with the 2006 Second Edition Topologically Integrated Geographic Encoding and Referencing (TIGER) streets layer.<sup>24</sup> This data set includes roadway centerlines that are classified by census feature class codes into various levels of primary, secondary, and local roadways. For this analysis, we focused on major roadways, including A1 (primary highways with limited access), A2 (primary roads without limited access), and A3 (secondary and connecting roads) roads<sup>25</sup> (see Figure 1). Although a lack of coverage required us to use road classifications rather than traffic volume to assign exposure, we note that in NC the mean annual average daily traffic (AADT) on major roads in 2004–2008 was almost 13,000, whereas the mean AADT on other small roads where traffic counts were measured was under 3000.<sup>26</sup> Smaller local and neighborhood roads were

not included, as the low traffic volumes on such roads could be considered to contribute to background exposure to traffic-related air pollution.

Data indicate that air pollution levels elevated near major roads decrease as distance to roadway increases, with pollution levels returning to background levels by 300 m,<sup>2</sup> although levels of some pollutants may remain higher over a greater distance.<sup>27</sup> Previous studies linking road proximity to birth outcomes have not used consistent categorizations for the exposure metric.<sup>18,17,21</sup> Therefore, we trichotomized the distance from each geocoded address to the centerline of the nearest A1, A2, or A3 road into <250 m, 250–500 m, and  $\geq 500$  m, hypothesizing that birth outcomes would be associated with proximity to a major road of <250 m but not with proximity beyond 250 m.

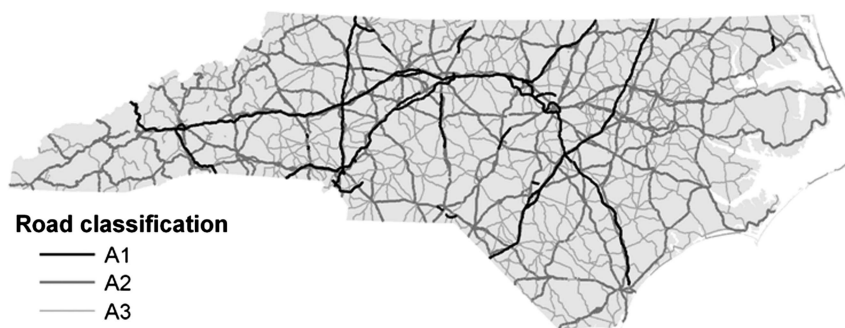
### Census Data

We constructed two tract-level covariates to control for population characteristics that may confound the effect of exposure to traffic-related air pollution on birth outcomes when using roadway proximity as a surrogate exposure measure. For example, individuals may be more likely to live closer to a major road in rural communities or in neighborhoods of lower socioeconomic status. We extracted tract-level population density as a measure of urbanization and median household income from the 2000 Census.<sup>28</sup> Each variable was categorized into three levels based on tertiles across all tracts in the State of North Carolina. Population density ranged from 154 to 1321 people per square meter in urban tracts (highest tertile) and from 9 to 69 people per square meter in rural tracts (lowest tertile), with suburban tracts having between 70 and 153 people per square meter. Tracts in the lowest tertile of socioeconomic status had a median household income under \$31,200 and tracts in the highest tertile of socioeconomic status had a median household income over \$37,400.

### Statistical Analysis

We considered an array of measures of fetal growth and pregnancy outcomes, including standard public health measures of adverse birth outcomes. On continuous scales, we modeled birth weight (in grams) and birth weight percentile for gestational age (proc glimmix in SAS 9.2). We also fit logistic models for the binary adverse outcomes of LBW (<2500 g), very LBW (VLBW; <1500 g), PTB (<37 weeks), late PTB (34–36 weeks), very PTB (VPTB; <34 weeks), SGA (SGA; <10<sup>th</sup> percentile of birth weight for gestational age), and gestational hypertension (GH; GH and/or pre-eclampsia reported; proc glimmix in SAS 9.2). Births reporting maternal chronic hypertension were excluded from models for GH and births at <34 weeks (VPTB) were excluded from models for late PTB. In order to account for within-tract correlation, models allowed for a random intercept for each tract.

All models controlled for maternal race, maternal age, maternal education, maternal marital status, maternal tobacco use during pregnancy, maternal nativity, parity, season of birth, infant sex (not included in GH models), tract-level urbanization, and tract-level median income. Maternal race/ethnicity was categorized as NHW (reference), NHB, or H.



**Figure 1.** Major roads by classification into A1 (primary highways with limited access), A2 (primary roads without limited access), and A3 (secondary and connecting roads) roads.

Given the non-linear relationship between maternal age and pregnancy outcomes, we categorized maternal age into 5-year age groups: 15–19, 20–24, 25–29, 30–34, 35–39, and 40–44 years. Parity was entered into the models as an indicator for first birth. Maternal educational attainment was defined as <9<sup>th</sup> grade, some high school (9<sup>th</sup>–11<sup>th</sup> grade), completed high school (12<sup>th</sup> grade), some college (13–15 years of education), and completed college (16 or more years of education). Maternal nativity was dichotomized as US-born and foreign-born. Season of birth was categorized as winter (December, January, February), spring (March–May), summer (June–August), and fall (September–November).

We explored a number of variations to assess sensitivity of our results. To check for the impact of edge effects, which may cause misclassification of road proximity for women living near the boundary of NC, we ran the main models excluding any births to women residing within 500 m of the state border. We tested for interactions between road proximity and tract-level urbanization, tract-level SES, maternal education, and season of birth. In addition, we considered models with road proximity defined as the inverse distance to the nearest major roadway rather than as a categorical variable. These models were restricted to births within 500 m and 300 m of a major roadway, as exposures among more distant births, where air pollution levels have returned to background levels, should not be assigned different exposures based on road proximity. All models were also run using distance to A1 and A2 roadways only, in order to test the sensitivity of the results to our definition of major roadway. All statistical analyses were performed using SAS 9.2 (SAS Institute, Cary, NC, USA).

## RESULTS

After applying all exclusion criteria, our analysis included 468,517 births across the State of North Carolina between 2004 and 2008. General summary statistics for the sample by road proximity are provided in Table 1. Our data set predominantly consisted of women who were NHW (60%), under 30 years of age (66%), married (61%), had at least one previous birth (57%), had at least a high school level education (79%), and were born in the United States (82%). In addition, about 11% of the women reported tobacco use during the index pregnancy. Moving farther from major roadways, generally maternal education and age increased, and tract income increased.

Almost two-thirds of the births (65.8%) were to women residing  $\geq 500$  m from a major roadway, with 18.4% occurring among women residing <250 m from a major roadway. Tables 2 and 3 present summaries of each pregnancy outcome across demographic groups and proximity to major roadways. Pregnancy outcomes generally followed expected patterns across demographic groups, with higher rates of adverse outcomes characterized by NHB, young and advanced maternal age, unmarried, first births, and lower income communities. Overall, the mean birth weight was 3307 g, with mean birth weight increasing from 3274 to 3322 g as distance to major roadway increased. Birth weight percentile for gestational age followed a similar pattern in relation to road proximity. With the exception of GH, VLBW, and VPTB, the rates of adverse outcomes (LBW, PTB, late PTB, and SGA) decreased as distance between maternal residence and a major roadway increased.

In multiple regression models for the continuous outcomes of birth weight and birth weight percentile for gestational age, proximity to major roadways was not significantly associated with the births outcomes at the 0.05 significance level. Table 4 presents the modeled mean birth weight (in grams) and birth weight percentile for gestational age for each road proximity category. Although the 95% confidence intervals for these modeled means overlap, the differences between the modeled mean birth weight for <250 m and the modeled means for both of the more distant categories were marginally significant ( $P < 0.1$ ).

Odds ratios and 95% confidence intervals for pairwise comparisons of the three levels of road proximity as they relate to each of the binary pregnancy outcomes are presented in

Table 5. Note, this table does not report results for models of VLBW, as the small number of cases of VLBW prevented the model with a random effect for each tract from converging. In models controlling for maternal and infant characteristics, as well as tract-level urbanization and income, proximity to a major roadway was associated with increased odds of LBW, PTB, and late PTB ( $P < 0.05$ ). For each of these outcomes, the model results highlight <250 m from a major roadway as the area of concern. In each case, women residing within 250 m of a major roadway were at 3–5% increased odds of the adverse outcome compared with women living farther from a major roadway, whereas there was no significant difference in the odds of the adverse outcome between women residing 250–500 m *versus*  $\geq 500$  m from a major roadway. Similar findings were seen in models excluding births within 500 m of the state border and when major roads were defined as A1 and A2 roads only.

For the outcomes associated with road proximity (LBW, PTB, and late PTB), interactions between road proximity and tract-level urbanization, tract-level SES, maternal education, and season of birth were assessed for each pregnancy outcome. None of these interaction terms showed a consistent signal.

In order to assess alternative forms of the relationship between pregnancy outcomes and proximity to major roadways, we fit models with road proximity defined as the inverse distance to the nearest major roadway rather than as a categorical variable. These models were restricted to births within 500 m and 300 m of a major roadway because exposures among more distant births, where air pollution levels have returned to background levels, should not be assigned different exposures based on road proximity. Inverse distance was significantly associated with VPTB and VLBW ( $P < 0.05$ ). In both cases, living closer to a major roadway was associated with slightly increased risk of the adverse outcome.

## DISCUSSION

Our analyses demonstrate an association between proximity to major roadways and pregnancy outcomes, especially LBW, PTB, and late PTB. Our findings on LBW are consistent with studies that have previously assessed the relationship between LBW and proximity to roadways.<sup>18,19,22</sup> Our findings on elevated risk for PTB associated with proximity to major roadways are consistent with some previous studies,<sup>18–21</sup> but contrasts with other studies that did not find a significant association.<sup>17,23</sup> We did not find a significant association between SGA and proximity to roadways, which is consistent with van den Hooven et al.,<sup>17</sup> but contrasts with other studies.<sup>18,22,23</sup> The one other study examining the association between GH and road proximity was consistent with our study in not finding a significant association.<sup>17</sup> Previous studies have been limited to urban populations and have not used a consistent method for defining road proximity-based exposure metrics, making it difficult to thoroughly compare results.

There are important limitations to this study. First, we do not account for the density of roadways, which may be especially important in urban areas where even smaller roads (which were not captured in our selected metric) may be dense enough to create similar air pollution levels to areas near a single major road. Second, we did not use traffic count data. In North Carolina, these data are collected for road planning purposes and thus do not cover the entire state, nor are the roads assessed for traffic count selected randomly. As a result, traffic count data are much more likely to be collected in urban areas. So although traffic count data would be a helpful addition to our modeling, the available data are problematic. Third, we did not account for different types of traffic on different roads. Presumably automobile traffic generates a different pollutant profile than truck traffic.<sup>29</sup> Fourth, we do not consider meteorological conditions like prevailing wind direction to characterize exposure via roadways. Fifth, like other road proximity studies,<sup>3,19</sup> we cannot control for seasonal or yearly

**Table 1.** Demographic composition of births overall and by proximity to major roadway.

	<i>All</i>		<i>Proximity to A1, A2, or A3 road</i>					
			< 250 m		250–500 m		≥ 500 m	
	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%
Total	468,517		86,046		74,245		308,226	
<i>Maternal race/ethnicity</i>								
Non-Hispanic white	282,718	60.3	45,037	52.3	38,921	52.4	198,760	64.5
Non-Hispanic black	109,142	23.3	22,596	26.3	21,495	29.0	65,051	21.1
Hispanic	76,657	16.4	18,413	21.4	13,829	18.6	44,415	14.4
<i>Maternal age (years)</i>								
15–19	54,099	11.5	12,281	14.3	9757	13.1	32,061	10.4
20–24	126,985	27.1	27,842	32.4	22,448	30.2	76,695	24.9
25–29	128,856	27.5	23,199	27.0	20,028	27.0	85,629	27.8
30–34	102,874	22.0	14,866	17.3	14,461	19.5	73,547	23.9
35–39	47,465	10.1	6652	7.7	6402	8.6	34,411	11.2
40–44	8238	1.8	1206	1.4	1149	1.5	5883	1.9
<i>Maternal education</i>								
<9th grade	29,683	6.3	7950	9.2	5493	7.4	16,240	5.3
Some high school	70,920	15.1	16,649	19.3	13,118	17.7	41,153	13.4
Completed high school	131,734	28.1	27,288	31.7	22,184	29.9	82,262	26.7
Some college	105,305	22.5	18,333	21.3	15,831	21.3	71,141	23.1
Completed college	130,875	27.9	15,826	18.4	17,619	23.7	97,430	31.6
<i>Infant sex</i>								
Male	240,113	51.2	44,091	51.2	37,953	51.1	158,069	51.3
Female	228,404	48.8	41,955	48.8	36,292	48.9	150,157	48.7
<i>Maternal tobacco use during pregnancy</i>								
Yes	50,445	10.8	11,113	12.9	8243	11.1	31,089	10.1
No	418,072	89.2	74,933	87.1	66,002	88.9	277,137	89.9
<i>Maternal marital status</i>								
Unmarried	181,018	38.6	41,594	48.3	33,903	45.7	105,521	34.2
Married	287,499	61.4	44,452	51.7	40,342	54.3	202,705	65.8
<i>Maternal parity</i>								
First birth	199,387	42.6	36,942	42.9	31,623	42.6	130,822	42.4
Higher order birth	269,130	57.4	49,104	57.1	42,622	57.4	177,404	57.6
<i>Maternal nativity</i>								
US-born	384,223	82.0	66,625	77.4	59,250	79.8	258,348	83.8
Foreign-born	84,294	18.0	19,421	22.6	14,995	20.2	49,878	16.2
<i>Season of birth</i>								
Winter	113,764	24.3	20,817	24.2	18,153	24.5	74,794	24.3
Spring	114,515	24.4	20,952	24.3	17,987	24.2	75,576	24.5
Summer	120,804	25.8	22,098	25.7	19,228	25.9	79,478	25.8
Fall	119,434	25.5	22,179	25.8	18,877	25.4	78,378	25.4
<i>Tract urbanization</i>								
Rural	124,041	26.5	24,242	28.2	13,730	18.5	86,069	27.9
Suburban	200,303	42.8	34,823	40.5	31,774	42.8	133,706	43.4
Urban	144,173	30.8	26,981	31.4	28,741	38.7	88,451	28.7
<i>Tract median household income</i>								
Low	112,080	23.9	30,158	35.0	24,304	32.7	57,618	18.7
Moderate	153,801	32.8	31,112	36.2	25,147	33.9	97,542	31.6
High	202,636	43.3	24,776	28.8	24,794	33.4	153,066	49.7

variation in traffic, which is especially important in models of pregnancy risk given the likely potential for particular windows of vulnerability during different stages of pregnancy. This consideration is at least partially mitigated by the fact that we have a very large sample size of women who are getting pregnant and giving birth throughout the year. Sixth, we use the address given to

representatives from the state registrar at the time of birth. We are unable to assess from such registry data whether women moved during pregnancy, nor do we have an assessment of how much time women spent during their pregnancies at the given address. Seventh, our geocoding rates are not as good in rural areas (64.2%) compared with urban areas (92.3%). And finally, proximity



**Table 2.** Pregnancy outcomes across demographic groups.

	% LBW	% VLBW	% PTB	% Late PTB	% VPTB	% SGA	% GH	Mean BWT (SD)	Mean BWT percentile for GA (SD)
Total	6.8	1.1	10.5	8.1	2.6	10.2	5.5	3307 (571)	48.6 (28.7)
<i>Maternal race/ethnicity</i>									
Non-Hispanic white	5.5	0.8	9.1	7.1	2.0	8.1	5.6	3376 (553)	52.0 (28.4)
Non-Hispanic black	11.6	2.2	14.6	10.0	4.6	16.1	6.1	3114 (603)	39.66 (27.6)
Hispanic	5.0	0.7	9.9	7.7	2.2	9.3	3.7	3330 (526)	48.6 (28.2)
<i>Maternal age (years)</i>									
15–19	9.8	1.5	13.3	9.5	3.8	15.5	6.1	3158 (563)	40.2 (27.4)
20–24	7.7	1.2	10.9	8.1	2.8	12.3	5.4	3248 (561)	44.8 (28.2)
25–29	6.0	1.0	9.5	7.3	2.3	9.0	5.3	3338 (560)	49.9 (28.4)
30–34	5.5	1.0	9.3	7.1	2.2	7.5	5.1	3387 (566)	53.2 (28.4)
35–39	6.3	1.1	11.1	8.5	2.6	7.3	5.6	3380 (591)	54.2 (28.7)
40–44	8.2	1.7	13.8	10.1	3.7	8.7	6.6	3316 (629)	52.3 (29.0)
<i>Maternal education</i>									
<9th grade	6.1	0.9	11.2	8.6	2.6	10.7	3.7	3296 (542)	47.2 (28.5)
Some high school	9.4	1.4	12.9	9.3	3.5	14.8	5.0	3185 (571)	42.1 (28.2)
Completed high school	8.1	1.4	11.6	8.5	3.1	12.0	5.7	3255 (582)	46.0 (28.7)
Some college	6.6	1.2	10.5	7.9	2.6	9.3	6.5	3323 (578)	49.8 (28.6)
Completed college	4.5	0.7	8.0	6.3	1.7	6.3	5.0	3417 (540)	54.1 (27.9)
<i>Infant sex</i>									
Male	6.3	1.1	11.0	8.2	2.7	9.9	5.5	3364 (581)	48.7 (28.6)
Female	7.4	1.1	10.0	7.5	2.5	10.4	5.4	3248 (554)	48.5 (28.7)
<i>Maternal tobacco use during pregnancy</i>									
Yes	12.4	1.7	13.6	9.8	3.8	19.5	5.0	3091 (575)	37.2 (27.4)
No	6.2	1.1	10.1	7.6	2.5	9.0	5.5	3334 (565)	50.0 (28.5)
<i>Maternal marital status</i>									
Unmarried	9.5	1.6	12.9	9.2	3.7	14.2	5.6	3190 (583)	42.5 (28.2)
Married	5.2	0.8	9.0	7.1	1.9	7.6	5.3	3382 (551)	52.4 (28.3)
<i>Maternal parity</i>									
First birth	8.1	1.4	10.7	7.8	2.9	12.4	7.7	3258 (582)	45.0 (28.4)
Higher order birth	5.9	0.9	10.4	8.0	2.4	8.4	3.8	3344 (560)	51.2 (28.6)
<i>Maternal nativity</i>									
US-born	7.3	1.2	10.7	8.0	2.7	10.4	5.8	3300 (580)	48.4 (28.7)
Foreign-born	4.9	0.7	9.5	7.4	2.1	9.0	3.6	3343 (529)	49.3 (28.2)
<i>Season of birth</i>									
Winter	7.0	1.1	10.8	8.1	2.7	10.4	5.6	3299 (572)	48.2 (28.7)
Spring	6.6	1.1	10.6	7.9	2.7	9.7	5.6	3316 (571)	49.2 (28.6)
Summer	6.9	1.1	10.6	8.0	2.6	10.1	5.2	3308 (573)	48.7 (28.7)
Fall	6.8	1.1	10.0	7.5	2.5	10.4	5.4	3306 (569)	48.2 (28.7)
<i>Tract urbanization</i>									
Rural	6.9	1.1	10.8	8.2	2.7	10.3	6.2	3308 (572)	49.0 (28.8)
Suburban	6.5	1.1	10.2	7.7	2.5	9.5	5.3	3324 (569)	49.4 (28.6)
Urban	7.3	1.2	10.7	7.9	2.8	10.9	5.0	3283 (574)	47.1 (28.5)
<i>Tract median household income</i>									
Low	8.6	1.4	12.3	9.0	3.3	12.7	5.7	3230 (585)	44.9 (28.7)
Moderate	7.1	1.2	10.8	8.1	2.7	10.7	5.9	3293 (572)	47.9 (28.7)
High	5.6	0.9	9.3	7.1	2.1	8.3	4.9	3361 (557)	51.1 (28.4)

Abbreviations: BWT, birth weight; GH, gestational hypertension; Late PTB, late preterm birth (34–36 weeks gestation); LBW, low birth weight (<2500 g); PTB, preterm birth (<37 weeks gestation); SGA, small for gestational age (<10th percentile of birth weight for gestational age); VLBW, very low birth weight (<1500 g); VPTB, very preterm birth (<34 weeks gestation).

to roadway may be measuring noise pollution rather than or in addition to air pollution.

Despite these limitations, our study provides important insights about the relationship between air pollution and pregnancy outcomes. The study includes all North Carolina births, not just those at a particular hospital or in a particular metro area. Previous road proximity studies have all been restricted to such catchment

areas. We also did not need to limit our analysis to those women living near an air monitoring station. Such stations are sited for regulatory purposes and tend to be located in urban areas or along major highways,<sup>30</sup> limiting the geographic scope of analyses employing this method for estimating exposure, as well as increasing exposure measure error. Modeling approaches (which can include temporal aspect-like monitoring data) can provide

**Table 3.** Pregnancy outcomes by proximity to major roads.

	<i>All</i>	<i>Proximity to A1, A2, or A3 road</i>		
		<i>&lt; 250 m</i>	<i>250–500 m</i>	<i>≥ 500 m</i>
<i>N</i>	468,517	86,046	74,245	308,226
% Low birth weight (<2500 g)	6.8	7.6	7.2	6.5
% Very low birth weight (<1500 g)	1.1	1.2	1.3	1.1
% Preterm birth (<37 weeks)	10.5	11.5	10.9	10.2
% Late preterm birth	8.1	8.8	8.3	7.9
% Very preterm birth (<34 weeks)	2.6	2.9	2.9	2.5
% Small-for-gestational age	10.2	11.3	10.9	9.7
% Gestational hypertension	5.5	5.7	5.5	5.5
<i>Birth weight (g)</i>				
Mean	3307	3274	3286	3322
SD	571	577	576	568
<i>Birth weight percentile for gestational age</i>				
Mean	48.6	46.9	47.5	49.3
SD	28.7	28.7	28.7	28.6

**Table 4.** Modeled mean (and 95% confidence interval) birth weight (in g) and birth weight percentile for gestational age (in percentile-points) by road proximity.

<i>Outcome</i>	<i>Proximity to A1, A2, or A3 road</i>		
	<i>&lt; 250 m</i>	<i>250–500 m</i>	<i>≥ 500 m</i>
Birth weight (g)	3157 (3152, 3162)	3162 (3157, 3168)	3161 (3157, 3165)
Birth weight percentile for gestational age	41.2 (40.9, 41.4)	41.4 (41.1, 41.6)	41.3 (41.1, 41.5)

Models control for maternal race, age, education, parity, marital status, tobacco use, maternal nativity, season of birth, infant sex, tract median income, and tract urbanization, with a random intercept for each tract.

**Table 5.** Covariate-adjusted odds ratios (95% confidence interval) for binary pregnancy outcomes by road proximity.

<i>Outcome</i>	<i>Proximity to A1, A2, or A3 road</i>		
	<i>&lt; 250 m versus 250–500 m</i>	<i>&lt; 250 m versus ≥ 500 m</i>	<i>250–500 m versus ≥ 500 m</i>
Low birth weight (<2500 g)	1.05 (1.01, 1.09)**	1.03 (1.00, 1.06)*	0.98 (0.95, 1.01)
Preterm birth (<37 weeks)	1.04 (1.01, 1.08)**	1.04 (1.01, 1.07)**	1.00 (0.97, 1.02)
Late preterm birth (34–36 weeks)	1.05 (1.01, 1.09)**	1.04 (1.01, 1.07)**	0.99 (0.96, 1.02)
Very preterm birth (<34 weeks)	1.02 (0.96, 1.08)	1.03 (0.98, 1.08)	1.01 (0.96, 1.06)
Small-for-gestational age	1.01 (0.98, 1.05)	1.01 (0.99, 1.04)	1.00 (0.97, 1.02)
Gestational hypertension	1.02 (0.97, 1.06)	1.04 (1.00, 1.07)*	1.02 (0.98, 1.06)

\* $P < 0.1$ ; \*\* $P < 0.05$

Models control for maternal race, age, education, parity, marital status, tobacco use, maternal nativity, season of birth, infant sex (except in gestational hypertension model), tract median income, and tract urbanization, with a random intercept for each tract.

exposure estimates in areas not covered by monitoring networks,<sup>31</sup> but require detailed data inputs and are computationally complex. However, if we used monitoring data and limited ourselves to counties with PM<sub>2.5</sub> monitors, we would lose about 13% of the analyzed births. If we limited analyzed births to within 10 km of a PM<sub>2.5</sub> monitor, we would lose about two-third of our subjects.

In addition, using road proximity as a proxy for traffic-related air pollution reflects long-term exposure to a mixture of pollutants instead of one or several criteria air pollutants from the monitoring network. This also provides us with a smaller-scale variation in levels of air pollutants, as compared with the more regional measures calculable from the monitoring network data.

Finally, the road proximity metric is straightforward to construct, understand, and explain, with results offering guidance for studies that can more accurately characterize air pollution exposures. It may also represent a more general metric for maternal risk from traffic-related air pollution.

Using a population-level data set for the entire State of North Carolina, our analyses demonstrate that living in close proximity to major roadways is associated with elevated risk for LBW, PTB, and late PTB. This is notable given the relatively good air quality present throughout the state. (The EPA's most recent air quality attainment reports from 2006 and 2010 indicate that all of North Carolina is "in attainment" for particulate matter.<sup>32</sup>) Future research should explore whether road proximity can be used to

select individuals for participation in more detailed (and more expensive) personal exposure monitoring studies. In addition, this line of analysis should be pursued in other states — especially so in locations where ambient air quality is poorer — as well as with other health end points that might reasonably be hypothesized to be linked to air pollution exposures.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## ACKNOWLEDGEMENTS

This research was supported by funding for the Southern Center on Environmentally-Driven Disparities in Birth Outcomes provided by the US Environmental Protection Agency (RD-83329301).

## REFERENCES

- 1 Brunekreef B., and Holgate S.T. Air pollution and health. *Lancet* 2002; **360**(9341): 1233–1242.
- 2 Jerrett M., Arain A., Kanaroglou P., Beckerman B., Potoglou D., Sahuvaroglu T., et al. A review and evaluation of intraurban air pollution exposure models. *J Expo Anal Environ Epidemiol* 2005; **15**(2): 185–204.
- 3 Sram R.J., Binkova B., Djekic J., and Bobak M. Ambient air pollution and pregnancy outcomes: a review of the literature. *Environ Health Perspect* 2005; **113**(4): 375–382.
- 4 Hack M., Klein N.K., and Taylor H.G. Long-term developmental outcomes of low birth weight infants. *Future Child* 1995; **5**(1): 176–196.
- 5 Moster D., Lie R.T., and Markestad T. Long-term medical and social consequences of preterm birth. *N Engl J Med* 2008; **359**(3): 262–273.
- 6 Barker D.J. The intra-uterine origins of disturbed cholesterol homeostasis. *Acta Paediatr* 1999; **88**(5): 483–484.
- 7 Barker D.J., Martyn C.N., Osmond C., Hales C.N., and Fall C.H. Growth in utero and serum cholesterol concentrations in adult life. *BMJ* 1993; **307**(6918): 1524–1527.
- 8 Osmond C., Barker D.J., Winter P.D., Fall C.H., and Simmonds S.J. Early growth and death from cardiovascular disease in women. *BMJ* 1993; **307**(6918): 1519–1524.
- 9 Weiss J.L., Malone F.D., Emig D., Ball R.H., Nyberg D.A., Comstock C.H., et al. Obesity, obstetric complications and cesarean delivery rate — a population-based screening study. *Am J Obstet Gynecol* 2004; **190**(4): 1091–1097.
- 10 Damaceno-Rodrigues N.R., Veras M.M., Negri E.M., Zanchi A.C., Rhoden C.R., Saldiva P.H., et al. Effect of pre- and postnatal exposure to urban air pollution on myocardial lipid peroxidation levels in adult mice. *Inhal Toxicol* 2009; **21**(13): 1129–1137.
- 11 Fedulov A.V., Leme A., Yang Z., Dahl M., Lim R., Mariani T.J., et al. Pulmonary exposure to particles during pregnancy causes increased neonatal asthma susceptibility. *Am J Respir Cell Mol Biol* 2008; **38**(1): 57–67.
- 12 Auten R.L., Gilmour M.L., Krantz Q.T., Potts E.N., Mason S.N., and Foster W.M. Maternal diesel inhalation increases airway hyperreactivity in ozone exposed offspring. *Am J Respir Cell Mol Biol* 2011; **46**(4): 454–460.
- 13 Veras M., Damaceno-Rodrigues N., Caldini E., Maciel Ribeiro A., Mayhew T., Saldiva P., et al. Particulate urban air pollution affects the functional morphology of mouse placenta. *Biol Reprod* 2008; **79**(3): 578–584.
- 14 Rocha E., Silva I., Lichtenfels A.J., Amador Pereira L.A., and Saldiva P.H. Effects of ambient levels of air pollution generated by traffic on birth and placental weights in mice. *Fertil Steril* 2008; **90**(5): 1921–1924.
- 15 Mauad T., Rivero D., de Oliveira R., Lichtenfels A., Guimaraes E., de Andre P., et al. Chronic exposure to ambient levels of urban particles affects mouse lung development. *Am J Respir Crit Care Med* 2008; **178**(7): 721–728.
- 16 Wenzel S., and Holgate S.T. The mouse trap: it still yields few answers in asthma. *Am J Respir Crit Care Med* 2006; **174**(11): 1173–1176.
- 17 van den Hooven E.H., Jaddoe V.W., de K.Y., Hofman A., Mackenbach J.P., Steegers E.A., et al. Residential traffic exposure and pregnancy-related outcomes: a prospective birth cohort study. *Environ Health* 2009; **8**: 59.
- 18 Genereux M., Auger N., Goneau M., and Daniel M. Neighbourhood socioeconomic status, maternal education and adverse birth outcomes among mothers living near highways. *J Epidemiol Community Health* 2008; **62**(8): 695–700.
- 19 Wilhelm M., and Ritz B. Residential proximity to traffic and adverse birth outcomes in Los Angeles county, California, 1994–1996. *Environ Health Perspect* 2003; **111**(2): 207–216.
- 20 Yang C.Y., Chang C.C., Chuang H.Y., Ho C.K., Wu T.N., and Tsai S.S. Evidence for increased risks of preterm delivery in a population residing near a freeway in Taiwan. *Arch Environ Health* 2003; **58**(10): 649–654.
- 21 Yorifuji T., Naruse H., Kashima S., Ohki S., Murakoshi T., Takao S., et al. Residential proximity to major roads and preterm births. *Epidemiology* 2011; **22**(1): 74–80.
- 22 Brauer M., Lencar C., Tamburic L., Koehoorn M., Demers P., and Karr C. A cohort study of traffic-related air pollution impacts on birth outcomes. *Environ Health Perspect* 2008; **116**(5): 680–686.
- 23 Zeka A., Melly S.J., and Schwartz J. The effects of socioeconomic status and indices of physical environment on reduced birth weight and preterm births in Eastern Massachusetts. *Environ Health* 2008; **7**: 60.
- 24 US Census Bureau. 2006 Second Edition TIGER/Line Files. US Census Bureau, Washington, DC, 2007.
- 25 US Census Bureau. 2006 Second Edition TIGER/Line Technical Documentation. US Census Bureau, Washington, DC, 2007.
- 26 North Carolina Department of Transportation, Traffic Survey Group. AADT Traffic Volume Reports. [http://www.ncdot.gov/doh/preconstruct/tpb/traffic\\_survey](http://www.ncdot.gov/doh/preconstruct/tpb/traffic_survey) (last updated 2012).
- 27 Karner A.A., Eisinger D.S., and Niemeier D.A. Near-roadway air quality: synthesizing the findings from real-world data. *Environ Sci Technol* 2010; **44**(14): 5334–5344.
- 28 US Census Bureau. Census 2000 Summary File 3–NC. US Census Bureau, Washington, DC, 2002.
- 29 Brook J.R., Poirot R.L., Dann T.F., Lee P.K., Lillyman C.D., and Ip T. Assessing sources of PM<sub>2.5</sub> in cities influenced by regional transport. *J Toxicol Environ Health A* 2007; **70**(3–4): 191–199.
- 30 Diem J.E., and Comrie A.C. Predictive mapping of air pollution involving sparse spatial observations. *Environ Pollut* 2002; **119**(1): 99–117.
- 31 Ryan P.H., and Lemasters G.K. A review of land-use regression models for characterizing intraurban air pollution exposure. *Inhal Toxicol* 2007; **19**(Suppl 1): 127–133.
- 32 The Green Book Nonattainment Areas for Criteria Pollutants. <http://www.epa.gov/oaqps001/greenbk/index.html> (last updated 30 August 2011).